THE ICARUS T600 EXPERIMENT AT LNGS*

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Liquid Argon Time Projection Chambers (LAr-TPCs) is an exciting class of detectors designed for registration of very rare events, like neutrino interactions or nucleon decay. They offer good detection efficiency, excellent background rejection, bubble chamber quality images, very good particle identification and calorimetric reconstruction of particle's deposited energy. These capabilities made LAr-TPCs a very promising choice for neutrino physics experiments. In this paper, an overview of LAr-TPC ICARUS T600 detector and its achievements are presented.

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1. Introduction

The idea of a Liquid Argon Time Projection Chamber was first proposed by Rubbia in 1977 [1] as a powerful detection technique which provides a three dimensional (3D) imaging of any ionizing event. In this type of detectors, liquid argon (LAr) serves also as the neutrino target. Neutrinos passing through LAr interact with argon atoms and produce, among others, ionization particles and light. Charged particles propagate in an electric field through LAr and leave a path of ionization electrons. The ionization electrons induce current in the anodes wire planes and, finally, their charge is collected. The measurements of: (1) the wires signals and (2) ionization electrons drift time exploiting scintillation light prompt signal and electrons velocity provide all the information needed for the 3D reconstruction of an event. The usage of argon seems to be optimal, since it is dense (large neutrino cross sections), inert (ionization electrons can be drifted through it), and relatively cheap (for example much cheaper than liquid xenon). However, the LAr must be kept extremely pure, allowing the ionization electrons

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to drift across the Time Projection Chamber (TPC) without significant attenuation, as was recently shown by the ICARUS Collaboration [2]. In addition, LAr-TPCs provide a very good discrimination between electron and photon interactions, what is of great importance for neutrino experiments.

2. Detector overview

The ICARUS (Imaging Cosmic And Rare Underground Signal) Collaboration pioneered the LAr-TPCs and demonstrated its feasibility for a long-term underground operation. They have developed the LAr-TPC technology from prototypical dimensions to the mass of 760 tons of LAr with the so-called T600 detector [3], installed in the underground INFN-LNGS[1] Gran Sasso Laboratory.

The ICARUS T600 detector is the largest LAr-TPC ever built, with four TPC chambers and cryogenic system containing about 760 tons of LAr. The detector module comprises of a large cryostat splitted into two identical, adjacent half-modules. Their internal dimensions are $3.6 \times 3.9 \times 19.6\,\mathrm{m}^3$. Each filled with about 380 tons of ultra-pure LAr. Each half-module houses: (1) two TPCs which share a common cathode in the middle, (2) a field shaping system, (3) two arrays of photo-multiplier tubes (PMT), and (4) monitors and probes. Each TPC is made of three parallel planes of wires, 3 mm pitch and plane spacing, facing the drift region, with wires oriented vertically at 0 and ± 60 degrees. Globally, 53 248 wires with length up to 9 m are installed in the detector. By appropriate voltage biasing, the first two planes (called 'Induction 1' and 'Induction 2') provide signals in a non-destructive way. The third wire plane (called 'Collection') finally collects the charge. The distance between the cathode and the wire planes *i.e.* the maximum electron drift path, is 1.5 m with nominal electric field equal to $E_{\mathrm{d}} = 0.5\,\mathrm{kV/cm}$. The signals coming from each wire are independently digitized every 400 ns.

Position of the tracks along the drift coordinate was determined by combining the knowledge about the electron drift velocity $v_{\mathrm{d}} \sim 1.6\,\mathrm{mm}/\mu\mathrm{s}$ at $E_{\mathrm{d}} = 0.5\,\mathrm{kV/cm}$ and the measurement of the absolute time of an ionizing event. The last one is determined via the prompt scintillation light produced by charged particles in LAr. For these purposes, a total of 20 and 54 (9357FLA Electron Tubes [4]) PMTs were immersed in the LAr in the West and East cryostats respectively, deployed behind wire planes. To detect the prompt photon emission with $\lambda = 128\,\mathrm{nm}$ produced by charged particles interacting in the LAr volume, the PMT windows was coated with wavelength shifter (here tetra-phenyl-butadiene (TPB)).

[1] Instituto Nazionale di Fisica Nucleare — Laboratori Nazionali del Gran Sasso.

The electronics was designed to allow continuous read-out, digitization and independent waveform recording signals from each wire of the TPC. The overall gain was about 1000 electrons per ADC count, setting the signal of minimum ionizing particles to ~ 15 ADC counts with a dynamic range of about 100 minimum ionizing particles. The average electronic noise was measured to be well within expectations on practically all the $\sim 54\,000$ channels: 1500 electrons r.m.s. to be compared with $\sim 15\,000$ free electrons produced by minimum ionizing particles (m.i.p.) in 3 mm (S/N ~ 10). The obtained spatial resolution was ~ 1 mm^3. Identification of protons, kaons, pions and muons was obtained through energy deposited per track length unit ($\mathrm{d}E/\mathrm{d}x$) *versus* particle range, and by studying the decay/interaction topology. Electrons were identified by their characteristic electromagnetic showering. They can be, at the level of per-mil, distinguished from π_0 using $\mathrm{d}E/\mathrm{d}x$ comparison of gamma and electron at first few wires.

2.1. Cryogenic plant

Both modules were surrounded by thermal insulation in shape of evacuated honeycomb panels in order to ensure tight contained vessel [3]. Between the insulation and the aluminum containers a thermal shield was placed with circulated boiling nitrogen to intercept the heat and maintain uniform (within 1 K) and stable (at 89 K) temperature in the cryostat volume. Nitrogen used to cool the modules was stored in two tanks placed at the top of the detector ($2 \times 30\,\mathrm{m}^3$ of LN_2). At the beginning of the T600 detector installation, two half-modules were cooled down to 9 K in about 8 days, while injecting of ultra-pure argon gas to ensure uniform temperature throughout the whole detector. Both cryostats were filled in parallel with commercial LAr, at a rate of $\sim 1\,\mathrm{m}^3$/hour/cryostat. LAr was delivered with 47 trucks in about 2 weeks for a total amount of 610 511 argon liters. LAr was purified *in situ* before entering the detector. During the whole period, the four gaseous re-circulation systems were operating at maximum speed to intercept the impurities which could have come from degassing components of the detector. One month after filling, the forced liquid argon recirculation and purification started on both cryostats at the rate of $1\,\mathrm{m}^3$/hour/cryostat.

2.2. Purification in situ of LAr and electron lifetime

The T600 is a single phase detector thus for good operation requires a high purity of LAr. The presence of impurities (most of all O_2) causes electron trapping and leads to exponential electron signal attenuation along drift coordinate. Therefore, the level of electronegative impurities in LAr must be kept exceptionally low to ensure order of meters long, drift path of ionization e^- signal without attenuation. This requires the continuous recirculation and filtering the LAr. The solutions used for the LAr recirculation and purification systems in ICARUS, permitted to reach an extremely low level of electronegative impurities in LAr. The measured content of O_2-equivalent contamination was less than 40 ppts measured with cosmic muons (12% maximum charge attenuation on 1.5 m drift length). It corresponds to a free electron lifetime $\tau_e > 7$ ms (Fig. 1).

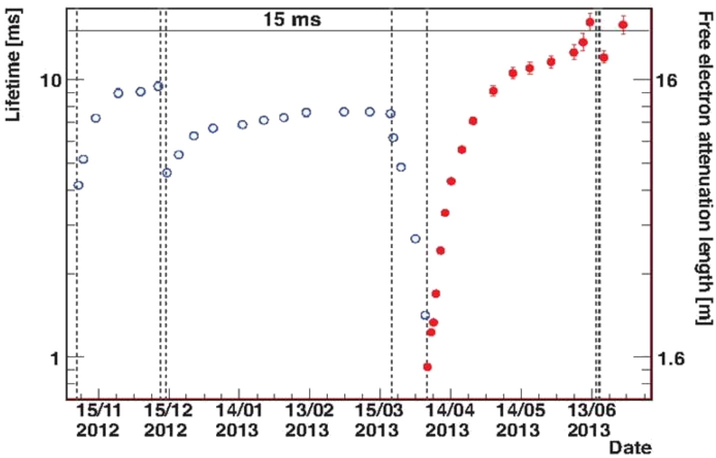

Fig. 1. (Colour on-line) Electron lifetime measurements for the East module during the last part of data taking. The full (red) points depict the measurements after the installation of a new pump.

After installation, a new non-immersed pump on East cryostat in 2013 measured content of O_2-equivalent contamination drop down to less than 20 ppts. It corresponds to $\tau_e > 15$ ms. This demonstrated that even several meters long electron drift paths in LAr are achievable and shown the effectiveness of single phase LAr-TPC technique paving the way to huge detectors with longer drift distance as required for *e.g.* LBNF/DUNE project. Details about electron lifetime and signal attenuation measurement can be found in [2], while cryogenic and purification systems are widely described in [6].

3. Atmospheric neutrino study

The ICARUS T600 detector collected cosmic ray data in two periods: (1) during CNGS beam data taking between October 2010 and December 3$^{\rm rd}$, 2012 and (2) after CNGS beam stop until June 26$^{\rm th}$, 2013. The exposure is equal to 0.48 kton year in the second period, whereas the total exposure is 0.73 kt year. For 2012–2013 run, the total 29 ± 3 atmospheric neutrino events with at least two and 45 ± 3 with one charged particle are expected.

Till now (end of 2017), about 42% of the data from 2012–2013 run have been analyzed. Taking into account (1) the scanning efficiency of $\sim 80\%$, (2) fiducial volume (5 cm from each TPC wall and 1.5 cm from the cathode *i.e.* $\sim 96\%$ of total LAr volume), (3) the noise removal about of 91% and (4) trigger efficiency of $\sim 85\%$, 3.6 ± 0.5 ν_μ and 2.7 ± 0.4 ν_e, multi-prong atmospheric neutrino events are expected. Although the selection procedure was fully automated, the analysis had to be complemented by visual human scanning in order to reject misidentified events and muons originated from outside of the detector and contributing to the background. The reduction to about 0.5% for multi-prong and 2% for one-prong candidates of events undergoing visual analysis was achieved. In the sample analyzed so far, 24 atmospheric neutrino candidates were found, which includes 4 identified as ν_e and 6 identified as ν_μ, which is in agreement with expectations. The atmospheric electron and muon neutrino interactions are shown in Fig. 2 and Fig. 3, respectively.

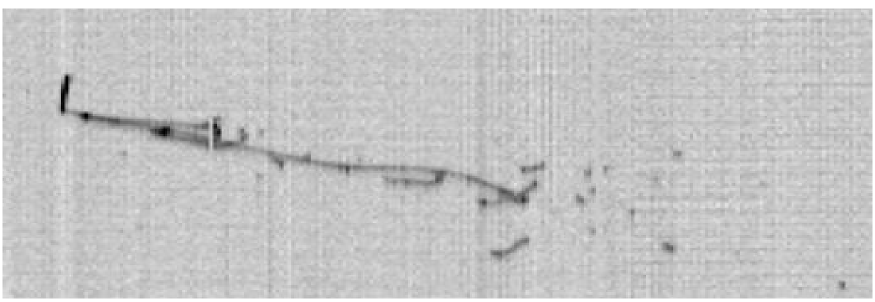

Fig. 2. An atmospheric ν_e event candidate with deposited energy $E_{\mathrm{DEP}} = 2.1\,\mathrm{GeV}$. Collection view is shown. The electron track, electromagnetic cascade and the hadronic part (short track) are clearly visible.

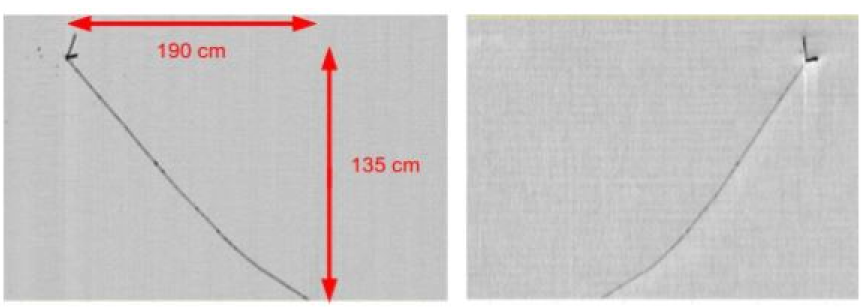

Fig. 3. An atmospheric ν_μ event candidate with deposited energy E_{DEP} equal to 630 MeV. Left: Collection view. Right: Induction 2 view. The muon exiting the detector and the hadronic part (two small tracks) are clearly visible.

4. ICARUS search for an LSND-like effect with CNGS beam

The LSND-like anomaly is related with possible presence of neutrino oscillation into sterile states. Such an oscillation was proposed by Pontecorvo [7]. The LSND Collaboration found excess of electron neutrino in muon–neutrino beam with $\langle E_\nu \simeq 30\rangle$ MeV and $L \simeq 30$ m. The LSND signal with $\bar{\nu_\mu}$ to $\bar{\nu_e}$ oscillation probability $P_{\bar{\nu_\mu}\to\bar{\nu_e}}$ equal to $2.64 \pm 0.67 \pm 0.45 \times 10^{-3}$ corresponds to an excess of $87.9 \pm 22.4 \pm 6.0$ events, namely a $3.8\,\sigma$ effect at distances L/E_ν of about 0.5–1.0 m/MeV.

Later, the anomaly was studied by a MiniBooNE [8] experiment using both ν and $\bar{\nu}$ beam with neutrinos from 8 GeV BNB beam and confirmed a ν oscillation signal (in ν and $\bar{\nu}$ channels) in the similar L/E_ν range at $3.8\,\sigma$.i.

The obtained results correspond to the signal within a wide interval $\Delta m^2_{\rm new} \simeq 0.01$–$1.0\,\mathrm{eV}^2$ and associated value of $\sin^2(2\theta_{\rm new})$ using the $\langle P_{\nu_\mu\to\nu_e}\rangle = \sin^2(2\theta_{\rm new})\sin^2(\frac{1.27\Delta m^2_{\rm new}L}{E_\nu})$ formula.

In comparison to experiments where LSND anomaly was observed, the ICARUS experiment had a much larger value of $L/E_\nu \simeq 36.5$ m/MeV, where the distance is equal to $L = 730$ km and mean E_ν about 20 GeV. It means that a hypothetical $\nu_\mu \to \nu_e$ LSND anomaly will produce very fast oscillation as a function of neutrino energy E_ν averaging closely to the value $\sin^2(1.27\Delta m^2_{\rm new}L/E_\nu) \simeq 1/2$ and wherefore approximately with the signal $\langle P_{\nu_\mu\to\nu_e}\rangle \simeq 1/2\sin^2(2\theta_{\rm new})$. This signal has to be compared with the small but significant background of other conventional neutrino sources.

The one of the main achievements of the ICARUS Collaboration is the excellent e/γ separation capability of the T600 detector, essential for the search of ν_e excess in the ν_μ CNGS beam, in order to verify the LSND hypothesis. During the CNGS campaign, seven ν_e events have been found, which is compatible with the expected backgrounds (ν_e beam contamination and Standard Model neutrino oscillations). Based on this number, the ICARUS Collaboration set limits on the oscillation probability (Fig. 4): $P_{\nu_\mu\to\nu_e} \leq 3.4 \times 10^{-3}$ at 90% C.L. and $P_{\nu_\mu\to\nu_e} \leq 7.60 \times 10^{-3}$ at 99% C.L. [9].

The results are in agreement with similar OPERA searches [10]. Therefore, the ICARUS could constrain the allowed parameters to a narrow region around $\Delta m^2_{\rm new} \sim 0.5$ eV^2, $\sin^2(2\theta_{\rm new}) \sim 0.005$, where all the contemporary results can be coherently accommodated at 90% C.L. To finally clarify the sterile neutrino hypothesis, the new measurement has been proposed. The ICARUS T600 together with two other detectors (SBND and MicroBooNE) will be a part of Short-Baseline Neutrino (SBN) Program at Fermilab [11], which is a joint proposal by three collaborations exploiting LAr-TPCs technique, to perform sensitive searches and clarification of LSND/MiniBooNE anomaly by precise and independent measurement of both ν_e appearance and ν_μ disappearance oscillation channels in the Booster Neutrino Beam (BNB).

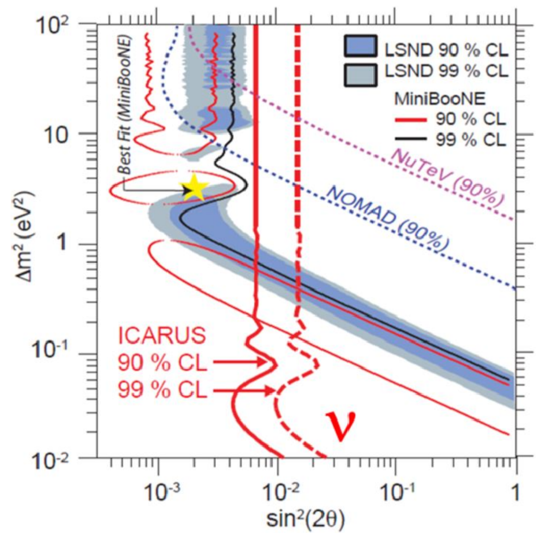

Fig. 4. Limits on the non-standard oscillation probability set by the ICARUS T600 Collaboration for ν [9].

5. Conclusions

The capabilities of ICARUS T600 detector make the LAr-TPC detectors a perfect tool for investigation of various aspects of very rare events physics. It is the largest LAr-TPC ever built but there are plans to construct detectors with even larger LAr volume (ktons range). However, substantial increase of volume may cause problems with LAr purification and stability of electric field. Despite of the so far success of the LAr-TPC, a worldwide efforts are taken or are planned to develop this detection technique. Should one think of increasing the size of a single phase (tens of kton) huge LAr container or about a modular structure with several separate vessels, each of a few ktons? Another solution is a double phase LAr-TPC detector in which ionizing electrons are extracted from the liquid phase, and their signal is amplified in the gaseous phase, as was proposed by the LAGUNA/LBNE Collaboration [12]. At the end of 2014, the ICARUS T600 detector has been transported to CERN for overhauling within the WA104 CERN neutrino program. After overhauling and upgrade, it has been moved (in 2017) to Fermilab to become a part of the Short-Baseline Neutrino program [11].

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